Numerical Investigation on Flow Field and Heat Transfer Phenomena in Multi-Hole Cooling Configurations

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Abstract

A transpiration cooled flat plate configuration is investigated numerically by application of a 3-D conjugate fluid flow and heat transfer solver, CHT-Flow. The geometrical setup and the fluid flow conditions are derived from modern gas turbine combustion chambers. The plate is composed of three layers, a substrate layer (CMSX-4) with a thickness of 2 mm, a bondcoat (MCrAlY) with a thickness 0,15 mm, and a thermal barrier coating (EB-PVD, Yttrium stabilized ZrO_2) with a thickness 0,25 mm, respectively.

The results of aerothermal calculations with adiabatic wall boundary conditions and the results of aerothermal calculation with fixed surface temperatures are compared to conjugate calculations that comprise both the fluid flow and the solid body. For conjugate calculations, there are no boundary conditions prescribed on the wall surfaces that are in contact with the fluid flow. The surface temperatures from the conjugate calculations are used as a boundary condition in the case of the aerothermal calculations with fixed surface temperatures. For the conjugate caluclations the numerical grid contains the cooling holes, the solid body, and the main flow area upon the plate. For the aerothermal investigations the grid contains the cooling holes and the main flow area.

The transpiration cooling is realized by finest drilled holes with a diameter of 0,2 mm that are shaped in the region of the thermal barrier coating. The holes are inclined with an angle of 30°. Two different configurations are investigated that differ in the shaping of the holes in their outlet region.

The numerical investigations focus on the deviation for the prediction of the thermal load of the solid body in the case of realistic cooling configuration that are induced by neglect of the heat transfer in the solid body. Due to a different prediction of the heat fluxes the structure of the cooling film deviates significantly between conjugate and aerothermal analysis. This investigations show that aerothermal investigation can only be a first step in a design process of cooling configurations.

Nomenclature

B	[m]	hole shaping parameter
D	[m]	hole diameter
L	[m]	distance of rows of cooling holes
T	[K]	temperature
p	[N/m^2]	pressure
v	[m/s]	velocity
x, y, z	[m]	Cartesian coordinate
α	[°]	angle of inclination
β_1, β_2	[°]	hole shaping parameters
ρ	[kg/m^3]	density

Indices

C	cooling fluid conditions
H	hot gas conditions
st	static
t	total
1	at inlet
2	at exit

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Introduction

Increasing the efficiency of modern gas turbines is still an important object of scientific research. One of the most important issues is the improvement of cooling technology both in the combustion chamber and in the vanes and blades of the turbine. Film cooling configurations have been investigated for several years. Concerning the CFD research in this subject, a bibliography (1971-1996) of the most important publications can be found in a study by Kercher [1]. Former numerical investigations focus on the development of the kidney vortices (Bergeles et al. [2]) in the case of flat plate cooling with one ejection hole. A detailed numerical analysis of the film cooling physics in the case of a flat plate with one row of cooling holes has been executed by McGovern and Leylek [3]. Those test cases are investigated by a aerothermal analysis of the fluid flow. The influence of heat conduction in the solid body is neglected.

Recently, even full-coverage film cooling calculations have been presented by Garg [4] and by Heidmann et al. [5]. These investigation show the aerothermal effects in the flow field of film cooled blades without consideration of the influence of heat transfer in the solid body.

In experimental and numerical analysis Fottner and Ganzert [6] investigated the flow field injections through inclined shaped holes in a cascade test tunnel. Here, the numerical investigations neglect the influence of the solid body, too. Although the numerical results show a large zone of recirculation in the cooling holes a good cooling configuration is stated. The accuracy of the results should be reviewed by application of a different numerical method with consideration of heat transfer in the solid body.

The conjugate analysis of the complete film cooling problem requires a high amount of computational time due to the necessity of high resolution grid that can compute the heat transfer into the solid body with accuracy. In the case of leading edge ejection the authors have shown that the influence of the solid body on the flow field is not negligible to calculate the surface temperature distribution of blades. In former publications the authors have proved that the conjugate method is an excellent tool for the design process of cooling configuration (Bohn and Moritz [7]).

Geometric Configuration

In this analysis a flat plate composed of three materials is investigated. The substrate layer is of the super alloy CMSX-4 and has a thickness of 2,0 mm (figure 1). The bondcoat consists of a MCrAlY layer with a thickness of 0,15 mm. The thermal barrier coating (TBC) is a Yttrium stabilized ZrO_2 layer with a tickness of 0,25 mm.

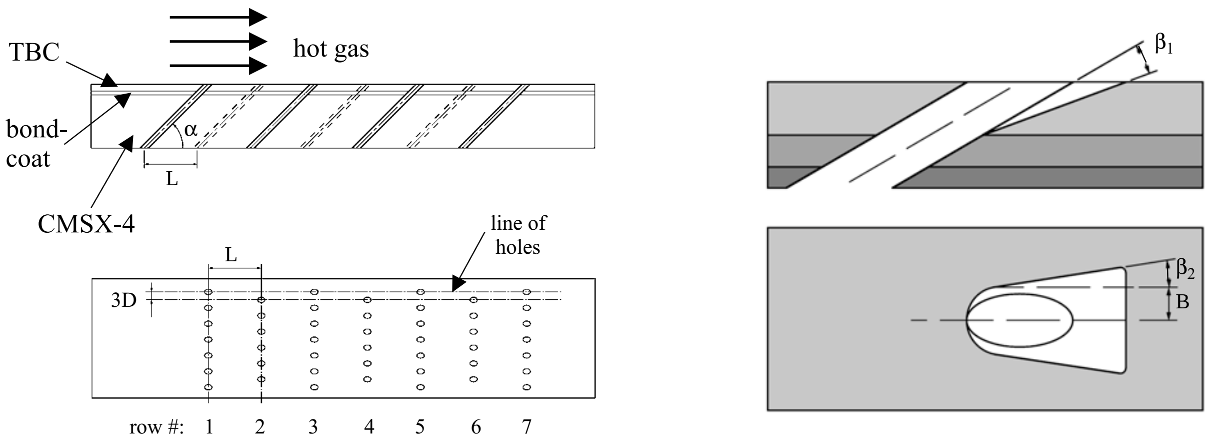
The plate is perforated with seven staggered rows of cooling holes with a diameter D=0,2 mm. The distance between two rows of holes is L=6D, the lines of holes have a separation of H=3D. Two different cooling configurations are investigated that vary the shaping of the outlet region of the cooling holes. The shaping is applied only in the region of the thermal barrier coating, the main parameters can be found on table 1.

Table 1: Geometry parameters of the investigated configurations

configuration	L	α	β_1	β_2	B
S30-06-F, S30-06-F-A	6D	30°	8°	0°	0,6088 D
S30-06-FL, S30-06-FL-A	6D	30°	8°	10°	0,6088 D

Numerical Method

The numerical scheme of the code works on the basis of an implicit finite volume method combined with a multi-block technique. The physical domain is divided into separate blocks and the full, compressible, three-dimensional Navier-Stokes equations are solved in the fluid blocks. The governing equations for the conservative variables are formulated in arbitrary, body-fitted coordinates in order to allow the simulation of complex geometries. The conservation equations are discretized implicitly to the first order in time making



General Geometric Parameters

Hole Shaping Parameters

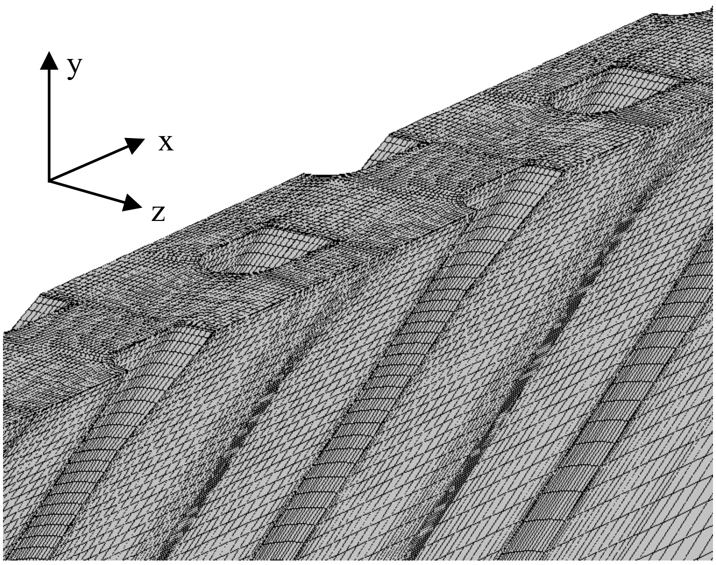
Figure 1: Geometry of the investigated plate

use of the Newton method (Schmatz [8]). Upwind discretization is used for the inviscid fluxes (Eberle et al. [9]). The viscous fluxes are approximated using central differences. The resulting system of linear equations is solved by a Gauss-Seidel point iteration scheme, allowing high vectorization on present day computers.

In the solid body region, the system of the governing equations is reduced to the Fourier equation. This equation is solved directly being coupled to the fluid flow region. The coupling of fluid blocks and solid body blocks is achieved via a common wall temperature, resulting from the equality of the local heat fluxes passing through the contacting cell faces. A more detailed description of the conjugate calculation method and its validation can be found in Bohn et al. [10, 11]. For the closure of the conservation equations the algebraic eddy-viscosity turbulence model by Baldwin and Lomax [12] is used.

Computational Grid and Boundary Conditions

Figure 2 shows, as an example, the numerical grid in the solid region of configuration S30-06-P-F. In total, it consists of 180 blocks (solid region and fluid flow) with approximately 1,200,000 points. The conjugate approach requires a high grid resolution in the boundary layers so that in the area of the cooling holes three O-type blocks are used which are arranged concentrically. To reduce the numerical effort only the area between the center lines of two lines of rows is investigated. At the z-planes through the middle axis of the holes a symmetry boundary condition is used.



configuration S30-06-F, S30-06-FL:
- 180 blocks
- 1 200 000 points

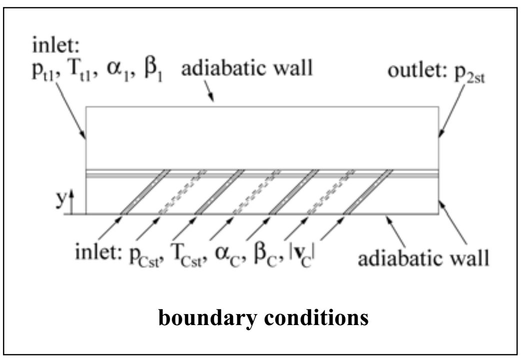


Figure 2: Computational grid (configuration S30-06-F; conjugate calculation) and boundary conditions

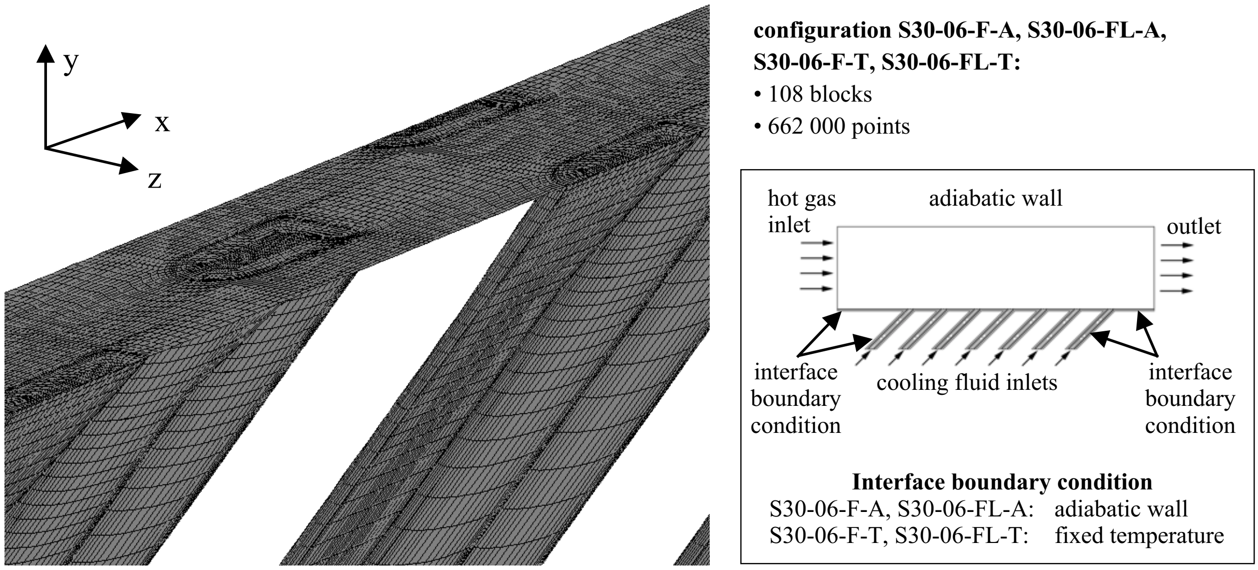


Figure 3: Computational grid (configuration S30-06-F-A or S30-06-F-T; areothermal calculations)

For configuration S30-06-F-A, S30-06-FL-A, S30-06-F-T and S30-06-FL-T the numerical grids were obtained by reducing the grids for the conjugate calculations to the fluid blocks. These grids consist of 108 blocks with approximately 662,000 points.

On the interfaces between fluid flow and solid body, these are the plate surface and the hole surfaces, adiabatic wall boundary conditions are applied for aerothermal calculation with adiabatic walls. In the case of aerothermal calculations with fixed wall temperatures on these walls the same temperatures are set as boundary conditions that were determined with the conjugate calculations. The aerothermal calculation grid on the plate surface and in the cooling holes is displayed in figure 3.

The inlet and outlet boundary conditions for the conjugate calculations are specified as sketched on the right-hand side in figure 2. In a distance of 5 mm from the plate surface a adiabatic wall boundary condition is set. At the lower edge of the plate, the cooling fluid flow is set by an inlet boundary condition at the cooling holes. For all computations the same boundary conditions were used that are shown in table 2. The values for temperature and pressure are derived from the flow conditions in modern gas turbine combustion chambers. The velocity of the hot gas stream yields to approximately 75 m/s which leads to a Ma-number of 0,1 in the main flow.

Results

In this chapter the results of the numerical investigations are shown and discussed. The results of the conjugate calculation are compared to the aerothermal calculations with adiabatic walls and fixed wall temperarures. The analyses focus on the varying prediction of the flow and heat transfer phenomena. In the first part, the structure and development of the cooling jets on the plate surface is investigated. Then the flow structure and temperature distribution in the shaping area of the cooling holes is analyzed. Finally, the temperature distribution and the heat transfer coefficients on the plate surface are discussed.

Table 2: Main boundary conditions

$\mathbf{p_{1t}}$	$20{,}1252 \cdot 10^5$	Pa
$\mathbf{T_{1t}}$	1575,93	K
$\mathbf{p_{2st}}$	$19{,}984 \cdot 10^5$	Pa
$\mathbf{p_{Cst}}$	$20{,}1 \cdot 10^5$	Pa
$\mathbf{T_{Cst}}$	723,15	K
$\mathbf{v_C}$ (approx.)	1,5	m/s

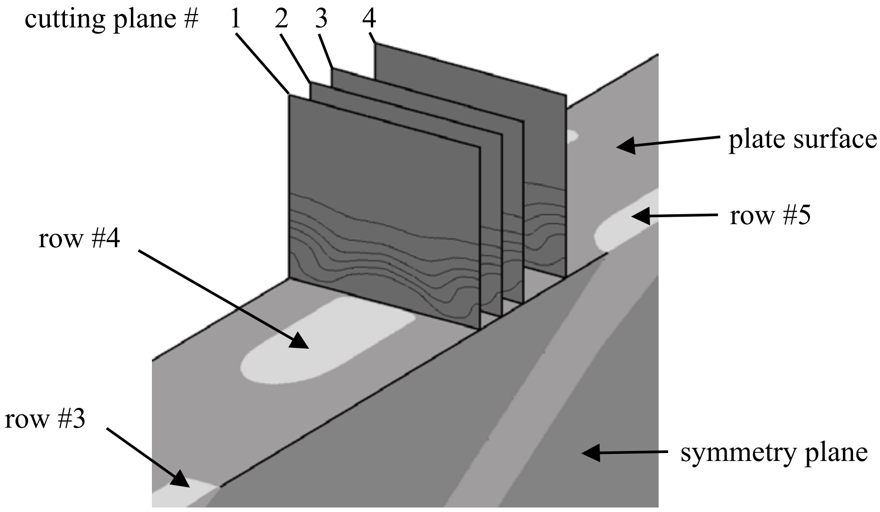


Figure 4: Position of the cutting planes on the plate surface

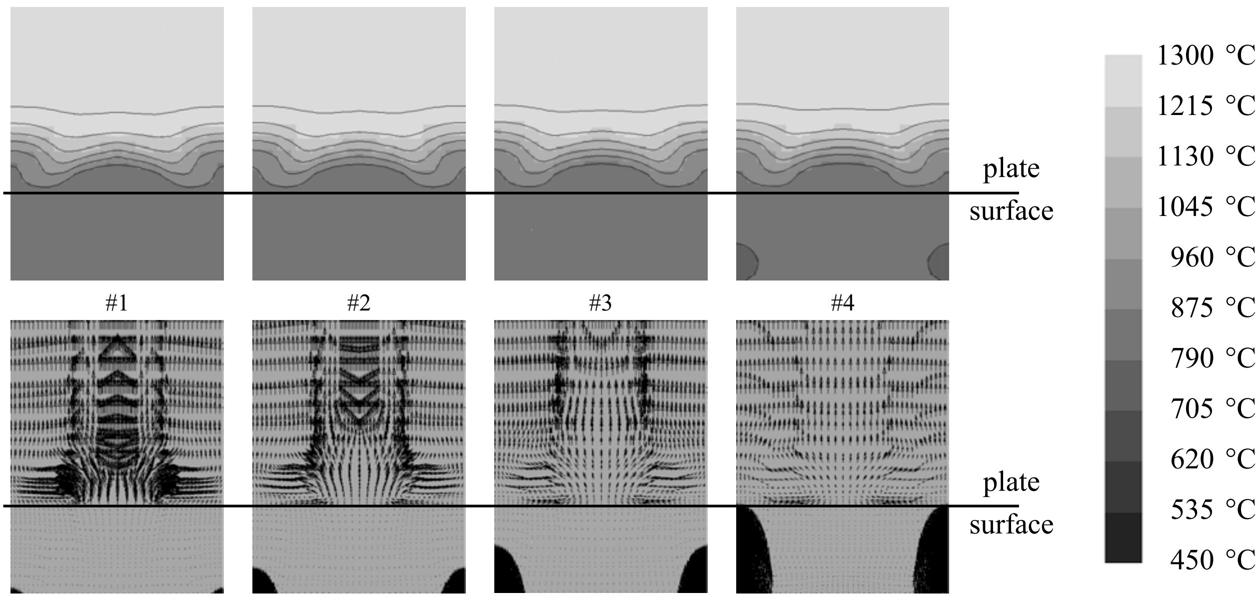


Figure 5: Temperature distribution and secondary flow vectors - conjugate calculation (S30-06-F)

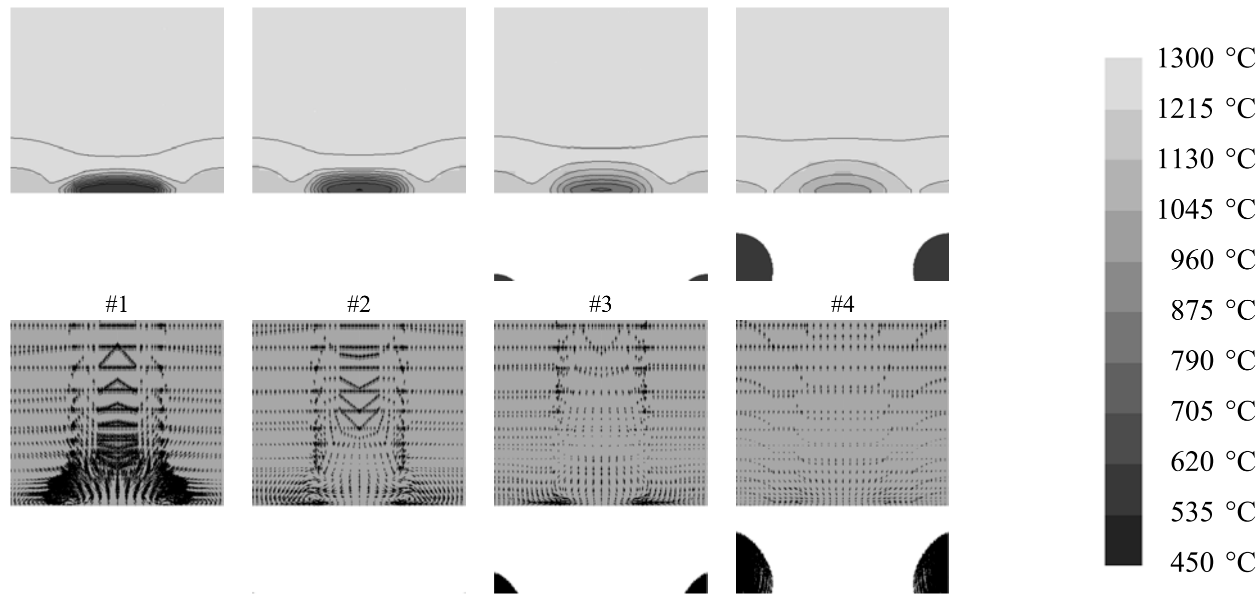


Figure 6: Temperature distribution and secondary flow vectors - adiabatic wall (S30-06-F-A)

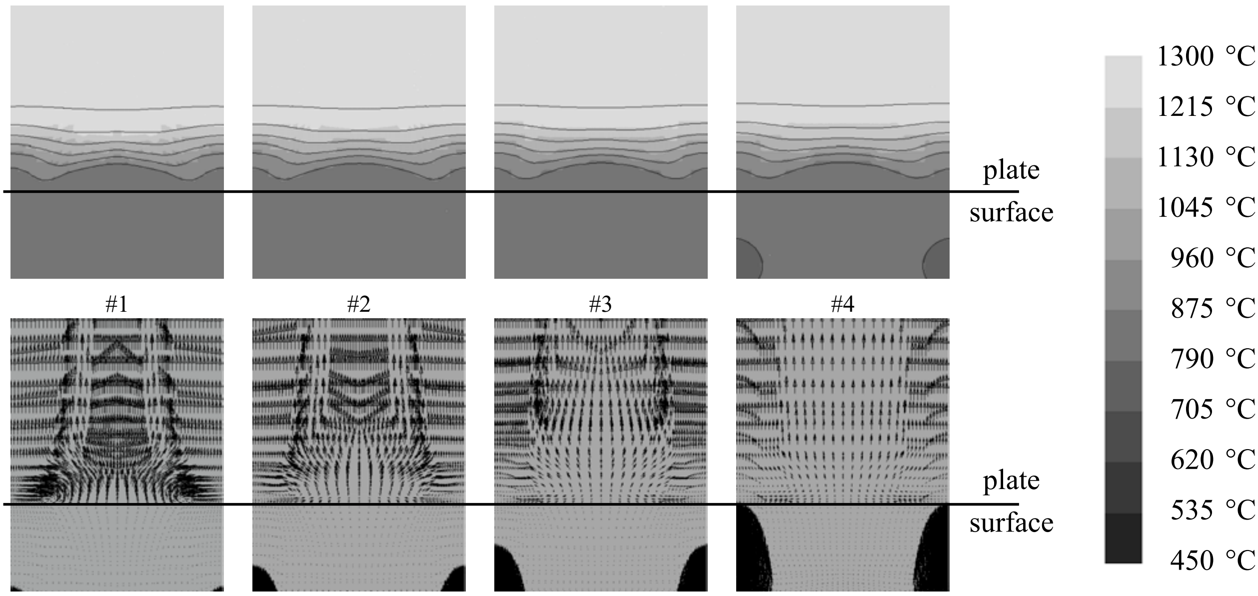


Figure 7: Temperature distribution and secondary flow vectors - conjugate calculation (S30-06-FL)

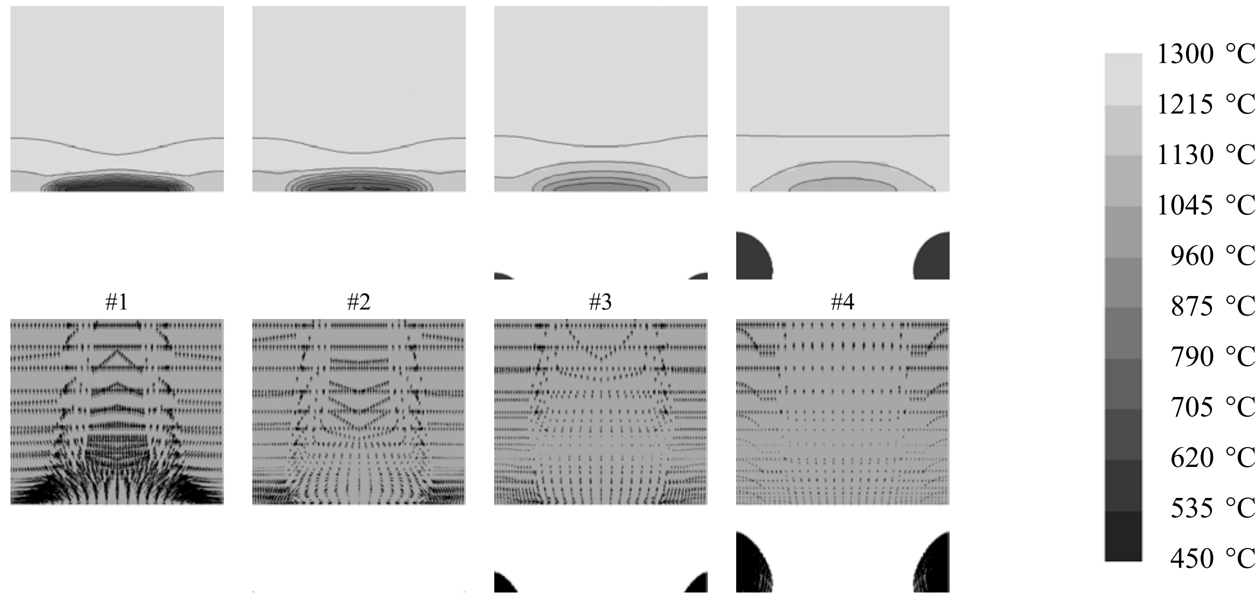


Figure 8:Temperature distribution and secondary flow vectors - adiabatic wall (S30-06-FL-A)

The investigated geometrical configurations with hole diameters of 0,2 mm have not been analyzed experimentally, yet. Beyond that, the experimental results that can be found in literature do not deal with the temperature ratios that are investigated in this paper.

Part I: Structure and development of the cooling jets

The structure and development of the cooling jets are analyzed by 2D cutting planes that are placed downstream the fourth row of cooling holes. Four cutting planes have been used. Their position on the plate surface is sketched in figure 4. For all results the scaling for the secondary flow vectors is set to the same value.

Figure 5 shows the cutting planes for configuration S30-06-F and figure 6 shows the results for configuration S30-06-F-A which has the same geometric design as configuration S30-06-F but it is calculated with adiabatic wall boundary conditions. The figures 7 and 8 give the same analysis for configuration S30-06-FL and S30-06-FL-A. The conjugate calculations (configurations S30-06-F and S30-06-FL) predict the development of a homogeneous cooling film an the plate surface as the authors have shown in preliminary

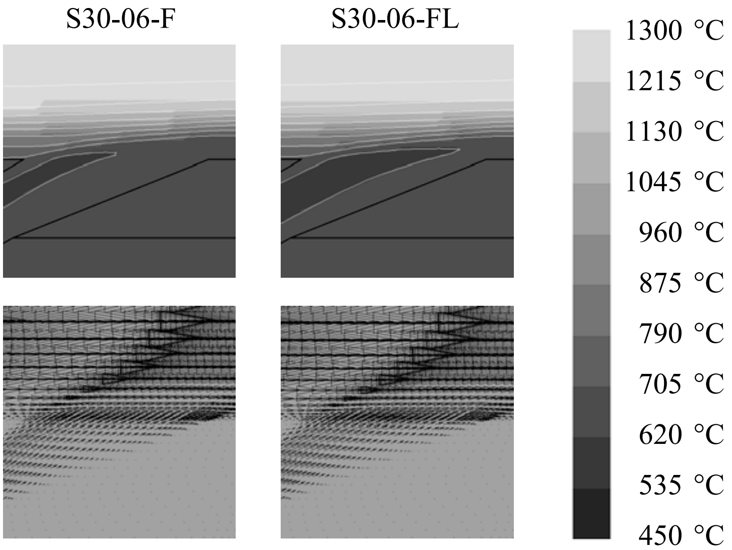


Figure 9: Temperature distribution and flow vectors in shaping area - conjugate calculation

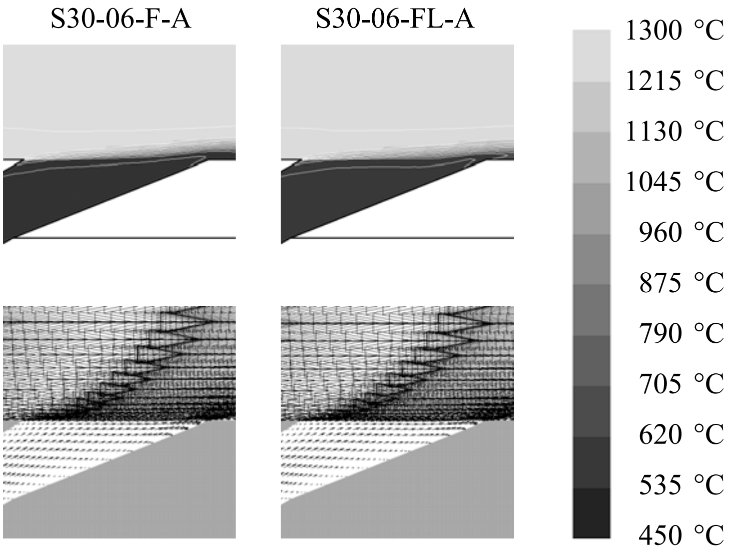


Figure 10: Temperature distribution and flow vectors in shaping area - adiabatic wall

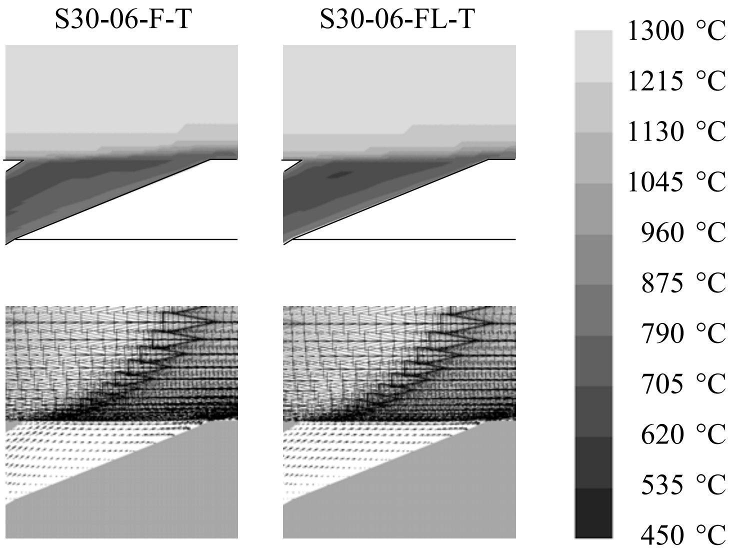


Figure 11: Temperature distribution and flow vectors in shaping area - fixed wall temperature

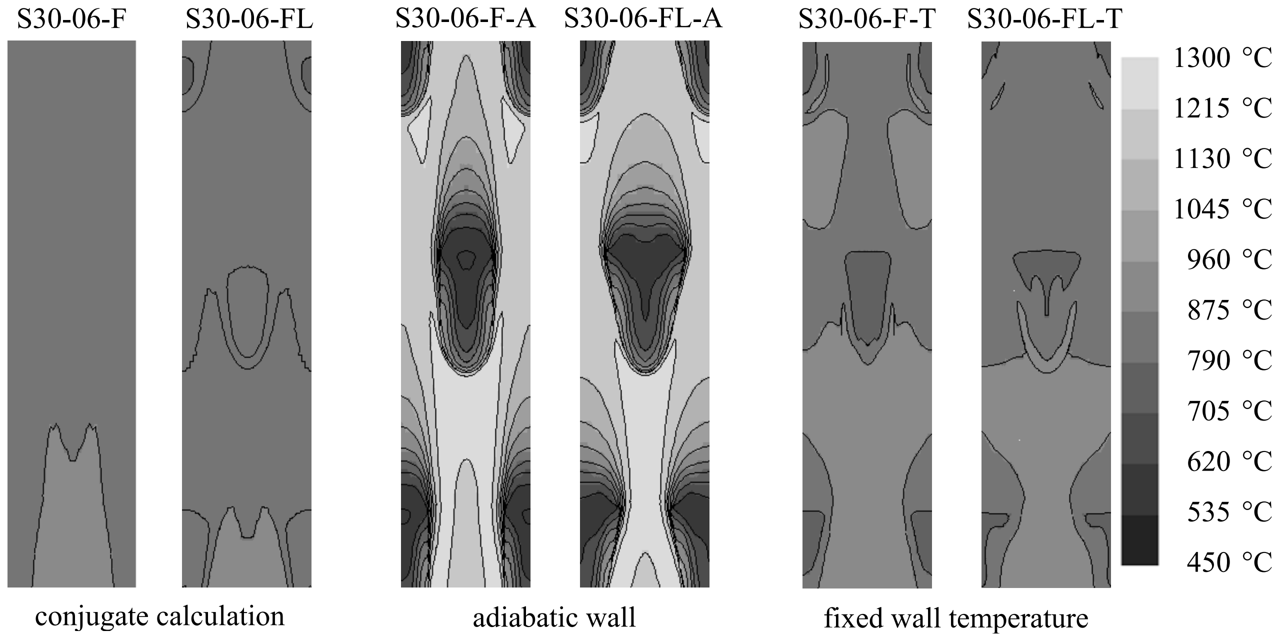


Figure 12: Temperature distribution on the plate surface

publications [13]. Due to the reduction of the kidney vortices (Ω_1 structure) nearly no contact of the hot gas flow to the plate surface can be detected.

In contrast, the aerothermal calculations with adiabatic wall boundary conditions (configurations S30-06-F-A and S30-06-FL-A) predict a smaller region on the plate surface that is protected by the cooling jets. A homogeneous cooling film is not to be found. The area of the plate surface in the close vicinity of the downstream edge of the cooling hole (cutting plane #1 and #2) is cooled with a higher efficiency than for conjugate calculations. The main reason for this effect is the missing increase of the cooling fluid temperature in the cooling holes. Therefore the mean cooling fluid temperature at the outlet of the cooling holes is nearly the same as at the cooling hole inlet. The cutting planes #3 and #4 show that in intensive mixture of the hot gas main flow and the cooling jets is predicted in the case of adiabatic wall calculations. This leads to a decrease of the cooling efficiency in that region compared to the conjugate calculations.

Part II: Flow structure in the shaping area

Figure 9 shows the 2D cutting planes at the middle axis in the shaping area at the outlet of the cooling hole in row #4 for the conjugate calculation. Figure 10 and figure 11 show the same cutting plane for the aerothermal calculations.

Regarding the temperature distribution (first row of images) it can be seen clearly that in the case of a aerothermal calculation with adiabatic walls the cooling fluid has nearly the same temperature at the hole outlet as at the inlet. Due to the reduced mixture of cooling fluid and hot gas the thickness of the cooling film is decreased. For aerothermal calculations with fixed wall temperatures nearly the same temperature distribution as for the conjugate calculation is to found in the cooling holes.

Contrary, the flow field in the cutting plane for both aerothermal calculations is nearly the same. Therefore, the mixture of cooling fluid and hot gas in the case of aerothermal calculations with fixed wall temperatures is reduced compared to the conjugate calculation, but it is increased compared to the adiabatic wall calculations.

Part III: Temperature distribution and heat transfer coefficient on plate surface

Figure 12 shows the temperature distribution on plate surface in the area from row #3 to row #5. The conjugate calculation predicts a lower mean surface temperature compared to the aerothermal calculation with adiabatic walls. Beyond that, the development of the a homogeneous cooling film for these calculation leads to a significant reduction of the temperature gradients. Altogether, it can be stated that the thermal load

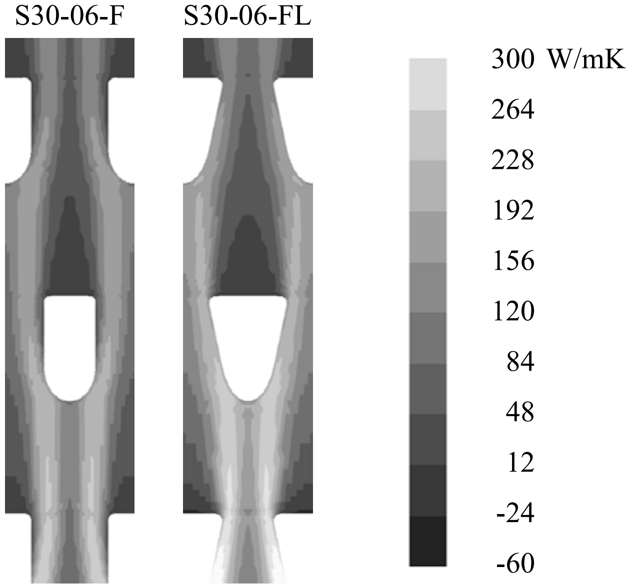


Figure 13: Heat transfer coefficient distribution on the plate surface (conjugate calculation)

on the plate surface is decreased remarkably in the case of conjugate calculations. Here the influence of the heat flux in the solid body considerable. For the aerothermal calculation with fixed wall temperatures both the mean surface temperature and the temperature gradients are reduced significantly compared to the adiabatic wall calculations. Only small deviations compared to the conjugate calculation can be stated.

In figure 13 the distribution of the heat transfer coefficient on the plate surface is shown for the same cutting planes as in figure 12. Ganzert and Fottner experimentally analyzed the heat transfer coefficient distribution on the suction side of a large scaled turbine blade with single row film cooling configuration [14]. The shape of the measurement results is quiet close to the conjugate calculations although additional effects are part of the experimental analysis (e.g. pressure gradients). It can be expected that the conjugate calculation predicts the distribution of the heat transfer coefficient with a higher accuracy than the aerothermal calculations. In further investigations, the influence of a modified boundary condition for the aerothermal calculations shall be analyzed. Beyond that, experimental results for these transpiration cooling configurations are necessary to evaluate the value of the temperatures and the heat transfer coefficients on the plate surface.

Conclusions

A transpiration cooled flat plate has been numerically analyzed by conjugate calculations and aerothermal calculations. For the aerothermal calculations adiabatic wall boundary conditions have been applied to the fluid/solid interfaces. Two different geometric configurations are part of this analysis. The flow conditions are derived from modern gas turbines combustion chambers.

The prediction of the secondary flow and the development of the cooling film on the plate surface is significantly different for the conjugate calculations and the aerothermal calculations. Due to the missing measurement results for these geometric configurations and the investigated temperatures, the numerical results can only be compared to experimental results in literature phenomenologically. The heat transfer coefficient distribution for the conjugate calculations shows the same shape as experimental results in literature. Therefore it can be expected that these results are more precise for the investigated configurations.

In further investigations, improved adiabatic wall boundary conditions shall be applied to the aerothermal calculation to investigate their influence on the results. Beyond, experimental results are necessary to evaluate the numerical results.

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References

[1] Kercher, D. M., 1998, "A Film-Cooling CFD Bibliography: 1971-1996", *Int. Journ. of Rot. Mach.*, **4 No. 1**, pp. 61-72

[2] Bergeles, G., Gosman, A.D., and Launder, B.E., 1976, "The Prediction of Three-Dimensional Discrete-Hole Cooling Processes", *Journal of Heat Transfer*, **98**, pp. 379-386

[3] McGovern, K.T., and Leylek, J.H., 1997, "A Detailed Analysis of Film Cooling Physics Part II. Compound-Angle Injection with Cylindrical Holes", *ASME 97-GT-270*

[4] Grag, V.K., 1999, "Heat Transfer on a Film-Cooled Rotating Blade", *ASME 99-GT-44*

[5] Heidmann, J.D., Rigby, D.L., and Ameri, A.A., 1999, "A 3D Coupled Internal/External Simulation of a Film-Cooled Gas Turbine", *ASME 99-GT-186*

[6] Fottner, L., and Ganzert, W., "Aerodynamische Optimierung der Kühlluft-Ausblasekonfigurationen fortschrittlicher Turbinenbeschaufelungen", *Informationstagung der FVV,* spring 2000, Frankfurt a. M.

[7] Bohn, D., and Moritz, N., 2000, "Influence of Hole Shaping of Staggered Multi-Hole Configurations on Cooling Film Development, *AIAA-paper 2000-2579*

[8] Schmatz, M.A, 1988, "Three-dimensional Viscous Flow Simulations Using an Implicit Relaxation Scheme", *Notes on Numerical Fluid-Mechanics (NNFM)*, **22**, Vieweg, Braunschweig, pp. 226-242

[9] Eberle, A., Schmatz, M.A., and Bissinger, N., 1990, "Generalized Flux Vectors for Hypersonic Shock-Capturing", *AIAA-paper 90-0390*

[10] Bohn, D., Bonhoff, B., Schönenborn, H., Wilhelmi, H., 1995, "Validation of a Numerical Model for the Coupled Simulation of Fluid Flow and Diabatic Walls with Application to Film-cooled Turbine Blades", *VDI-Berichte 1186*

[11] Bohn, D., Schönenborn, H., Bonhoff, B. and Wilhelmi, H., 1995, "Prediction of the Film-cooling Effectiveness in Gas Turbine Blades Using a Numerical Model for the Coupled Simulation of Fluid Flow and Diabatic Walls", *ISABE 95-7105*

[12] Baldwin, B. S., and Lomax, H., 1978, "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows", *AIAA-paper 78-257*

[13] Bohn, D., and Moritz, N., "Influence of Hole Shaping of Staggered Multi-Hole Configurations on Cooling Film Development", *AIAA-paper 2000-2579*

[14] Ganzert, W., and Fottner, L., "An Experimental Study on the Aerodynamics and the Heat Transfer of a Suction Side Film Cooled Large Scale Turbine Cascade", *ASME 99-GT-39*